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# A NEARBY GRB HOST PROTOTYPE FOR $Z \sim 7$ LYMAN-BREAK GALAXIES: SPITZER-IRS AND X-SHOOTER SPECTROSCOPY OF THE HOST GALAXY OF GRB 031203

D. WATSON,[1] J. FRENCH,[1] L. CHRISTENSEN,[2,3] B. O'HALLORAN,[4] M. MICHAŁOWSKI,[5] J. HJORTH,[1] D. MALESANI,[1] J. P. U. FYNBO,[1] K. D. GORDON,[6] J. M. CASTRO CERÓN[1,7] S. COVINO[8] R. F. REINFRANK[9,10]

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## ABSTRACT

Gamma-ray burst (GRB) host galaxies have been studied extensively in optical photometry and spectroscopy. Here we present the first mid-infrared spectrum of a GRB host, HG 031203. It is one of the nearest GRB hosts at $z = 0.1055$, allowing both low and high-resolution spectroscopy with *Spitzer*-IRS. Medium resolution UV-to-$K$-band spectroscopy with the X-shooter spectrograph on the VLT is also presented, along with *Spitzer* IRAC and MIPS photometry, as well as radio and sub-mm observations. These data allow us to construct a UV-to-radio spectral energy distribution with almost complete spectroscopic coverage from 0.3–35 $\mu$m of a GRB host galaxy for the first time, potentially valuable as a template for future model comparisons. The IRS spectra show strong, high-ionisation fine structure line emission indicative of a hard radiation field in the galaxy – in particular the [S IV]/[S III] and [Ne III]/[Ne II] ratios – suggestive of strong ongoing star-formation and a very young stellar population. The absence of any PAH emission supports these conclusions, as does the probable hot peak dust temperature, making HG 031203 similar to the prototypical blue compact dwarf (BCD) galaxy, II Zw 40. The selection of HG 031203 via the presence of a GRB suggests that it might be a useful analogue of very young star-forming galaxies in the early universe, and hints that local BCDs may be used as more reliable analogues of star-formation in the early universe than typical local starbursts. We look at the current debate on the ages of the dominant stellar populations in $z \sim 7$ and $z \sim 8$ galaxies in this context. The nebular line emission is so strong in HG 031203, that at $z \sim 7$, it can reproduce the spectral energy distributions of $z$-band dropout galaxies with elevated IRAC 3.6 and 4.5 $\mu$m fluxes without the need to invoke a 4000 Å break. Indeed, photometry of HG 031203 shows elevation of the broadband $V$-magnitude at a level similar to the IRAC elevation in stacked $z$-band dropouts, solely due to its strong [O III] line emission.

*Subject headings:* gamma-ray burst: general – gamma-ray burst: individual: GRB031203 – early universe – dark ages, reionisation, first stars – galaxies: dwarf – galaxies: ISM

## 1. INTRODUCTION

Long-duration gamma-ray bursts (GRBs) trace the formation of massive stars (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Bloom et al. 2002). They occur across a vast range of cosmic distances from $z = 0.0085$ (Galama et al. 1998) to $z = 8.2$ (Tanvir et al. 2009), and with a very high mean redshift ($\langle z \rangle = 2.2$ Fynbo et al. 2009). Their hosts therefore provide a unique way to select star-forming galaxies because, unlike other selection techniques, their selection is unrelated to the emission properties of the galaxies themselves.

Studies of GRB hosts have so far suggested that they are star-forming galaxies with relatively high specific star-formation rates and young stellar populations (Christensen et al. 2004; Castro Cerón et al. 2006; Savaglio et al. 2009; Svensson et al. 2010; Chary et al. 2002). However, it is worth bearing in mind that such general statements are still difficult to make in an absolute sense because of the potential bias introduced in sample selection because most GRB hosts have been selected up to now on the basis of localisations dependent on optical afterglows. Some attempts to address this essential question are being made with X-ray–selected samples (Malesani et al. 2009).

Optical spectroscopy in absorption using the afterglow (e.g. Fynbo et al. 2009), or occasionally in emission from the host galaxy itself where it is bright enough (e.g. Wiersema et al. 2007; Levesque et al. 2010) have indicated metallicities in GRB host galaxies that are relatively low, but not atypical of the population forming high-mass stars, at least at $z \gtrsim 2$ (Fynbo et al. 2006; Calura et al. 2009). One of the best-studied cases so far, because of its proximity at $z = 0.1055$, is the host of GRB 031203 (HG 031203, Prochaska et al. 2004). These studies (Prochaska et al. 2004; Margutti et al. 2007; Levesque et al. 2010; Han et al. 2010) have shown HG 031203 to be a relatively low metallicity system with a fairly high star-formation rate and a young stellar population. As with all optical studies, such analyses are dominated by the low-dust regions and may give an incomplete impression of the galaxy since a significant fraction of the stellar emission, particularly from young stars, may be re-processed by dust and emerge in

[1] Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark; darach, jens, malesani @dark-cosmology.dk
[2] Excellence Cluster Universe, Technische Universität München, Bolzmanstrasse 2, 85748 Garching, Germany
[3] European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany
[4] Astrophysics Group, Imperial College, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK
[5] Scottish Universities Physics Alliance, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK
[6] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[7] Herschel Science Centre (ESAC/ESA), Camino Bajo del Castillo, s/n, E-28.692 Villanueva de la Cañada (Madrid), Spain
[8] INAF/Osservatorio Astronomico di Brera, via Emilio Bianchi 46, 23807 Merate (LC), Italy
[9] Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
[10] School of Chemistry & Physics, The University of Adelaide, Adelaide, SA 5005, Australia

the mid- and far-infrared (IR).

To date, all spectroscopic studies of GRB host galaxies have been at optical or near-IR wavelengths. Here we present the first spectroscopic study of a GRB host galaxy in the mid-IR (5–40 $\mu$m) using the *Spitzer Space Telescope* (Werner et al. 2004) Infrared Spectrograph (IRS Houck et al. 2004). We also present an almost continuous spectral energy distribution (SED) for this galaxy from the ultraviolet through to the mid-IR (0.35–40 $\mu$m), with detections and upper limits at far-IR, sub-mm and radio wavelengths, the first such SED for a GRB host.

Uncertainties quoted are at the 68% confidence level for one interesting parameter unless otherwise stated. A cosmology where $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.73$ and $\Omega_\mathrm{m} = 0.27$ is assumed throughout.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. *X-shooter*

HG 031203 was observed during the commissioning of the second generation VLT instrument, X-shooter (D'Odorico et al. 2006) on 17 March 2009. X-shooter is a single object echelle spectrograph consisting of three arms which cover simultaneously the spectral range 300–2480 nm. The slit widths chosen during the observations were $1\farcs0$ in the UVB arm ($\Delta\lambda = 300$–$550$ nm), and $0\farcs9$ in the VIS ($\Delta\lambda = 550$–$1015$ nm) and NIR arms ($\Delta\lambda = 1000$–$2480$ nm). This instrument setup gives resolutions in the three arms of $R = 5100$, 8800, and 5600, respectively. The slit width matched the seeing during the observation. During the observations the slit was aligned along the parallactic angle. We obtained four 20 minute integrations on target, with offsets along the slit in a classic ABBA observing pattern. The UVB detector was binned by a factor of two in the spectral direction when the detectors were read out. With a $1''$ slit width in the UVB arm, the sampling for the full-width half-maximum of a line is 6 pixels, so a better signal-to-noise ratio per pixel is obtained in binned data.

Data reduction was performed with a preliminary version of the pipeline (Goldoni et al. 2006). Tracing the individual orders, wavelength calibration, and flat fielding were done using calibration frames obtained during the commissioning run. In the UVB and VIS data, subtraction of the sky background used a routine described in Kelson (2003), while the background in the NIR data was subtracted using the adjacent science exposures. Finally the individual orders were extracted and merged using a weighted mean combination scheme, resulting in a two-dimensional spectrum for each arm. Similar data reduction procedures were done for the HST white dwarf spectrophotometric standard star GD 71 which was used to flux calibrate the science data, and for an observation of the O8V star Hipparcos 69892, which provided a reference smooth spectrum for dividing out telluric absorption lines from the earth's atmosphere.

Further analysis of the data was performed with conventional IRAF routines. The four two-dimensional spectra were combined, and one-dimensional spectra were extracted using an aperture which matched the three arms. In the flux calibration of the observation, we included a correction for the atmospheric extinction using an extinction curve appropriate for Paranal.

### 2.2. Spitzer

The *Spitzer* photometric data on HG 031203 were obtained with IRAC (Fazio et al. 2004) at 3.6 and 5.8 $\mu$m with a 30 s frame time, and a total integration time of 360 s and MIPS (Rieke et al. 2004) at 24 $\mu$m also with 30 s integration times and a total observation time of $\sim 1350$ s. The data, under program 20370, were reduced as outlined in Castro Cerón et al. (2010).

**Table 1**
Spitzer-IRS observations of the host galaxy of GRB 031203

| Module | SH | LH | SL1 | SL2 | LL1 | LL2 |
|---|---|---|---|---|---|---|
| Integration Time (s) | 3656.9 | 1828.5 | 609.5 | 1828.5 | 314.6 | 943.7 |

The target was also observed spectroscopically, in staring mode using all four IRS modules; short-low (SL, 5.2–14.5 $\mu$m), long-low (LL, 14.0–38.0 $\mu$m), short-high (SH, 9.9–19.6 $\mu$m), and long-high (LH, 18.7–37.2 $\mu$m). The resolution of the low-resolution modules is $\sim$60–127, while that of the high-resolution modules is $\sim$600. Observations were carried out on 28 May 2005 (see Table 1).

Data from the short-low and short-high modules were preprocessed with the *Spitzer* Science Centre (SSC) data reduction pipeline version 15.3, while data from the long-low and long-high modules were processed with version 17.2.

For the high-resolution modules, spectra were extracted from each individual basic calibrated data (BCD) file using the Spitzer IRS Custom Extraction (SPICE) software. Prior to extraction of the spectra, data files were individually cleaned of rogue pixels using the IDL program IRSCLEAN version 1.9. The rogue pixel masks used for cleaning were a combination of the default campaign masks provided by the SSC and masks generated automatically by running IRSCLEAN's rogue pixel identification algorithm.

Individual spectra were subsequently combined with a clipped mean algorithm using the Spectral Modelling, Analysis, and Reduction Tool (SMART) developed by the IRS team (Higdon et al. 2004). The edges of each order were trimmed based on the wavelength calibration ranges provided in Table 5.1 of the IRS Data Handbook version 3.1. Since no sky measurements were taken, the contribution of the sky emission was not subtracted from the high-resolution spectra. No subtracting the sky background has a significant effect on the level of the continuum measured with the high-resolution modules. However, we use the high-resolution data only to extract emission line fluxes, not for the SED work, so that a continuum offset is not a significant issue. The fluxes obtained with the high-resolution modules are consistent with those retrieved from the low resolution spectra.

For the low-resolution data, we made use of pipeline coadded, sky-subtracted products. These files result from coadding the data from each nod position, then subtracting each nod position from the other in order to subtract the background. The spectra were cleaned for rogue pixels and optimally extracted to produce the final 1-D spectra.

The source was also observed with MIPS in SED mode. The data were reduced in a standard way, as described in van Loon et al. (2010).

### 2.3. *Sub-mm–radio*

We obtained radio continuum observations of HG 031203 on 26 January 2008 using the Australia Telescope Compact Array (ATCA) in configuration 6A, with antennae positioned on both east-west and north-south tracks, and baselines of 60–4500 m. Simultaneous observations were made at 20 cm (1.39 GHz) and 13 cm (2.37 GHz), with a bandwidth of 128 MHz at each frequency. A total of 7 hr of on-source

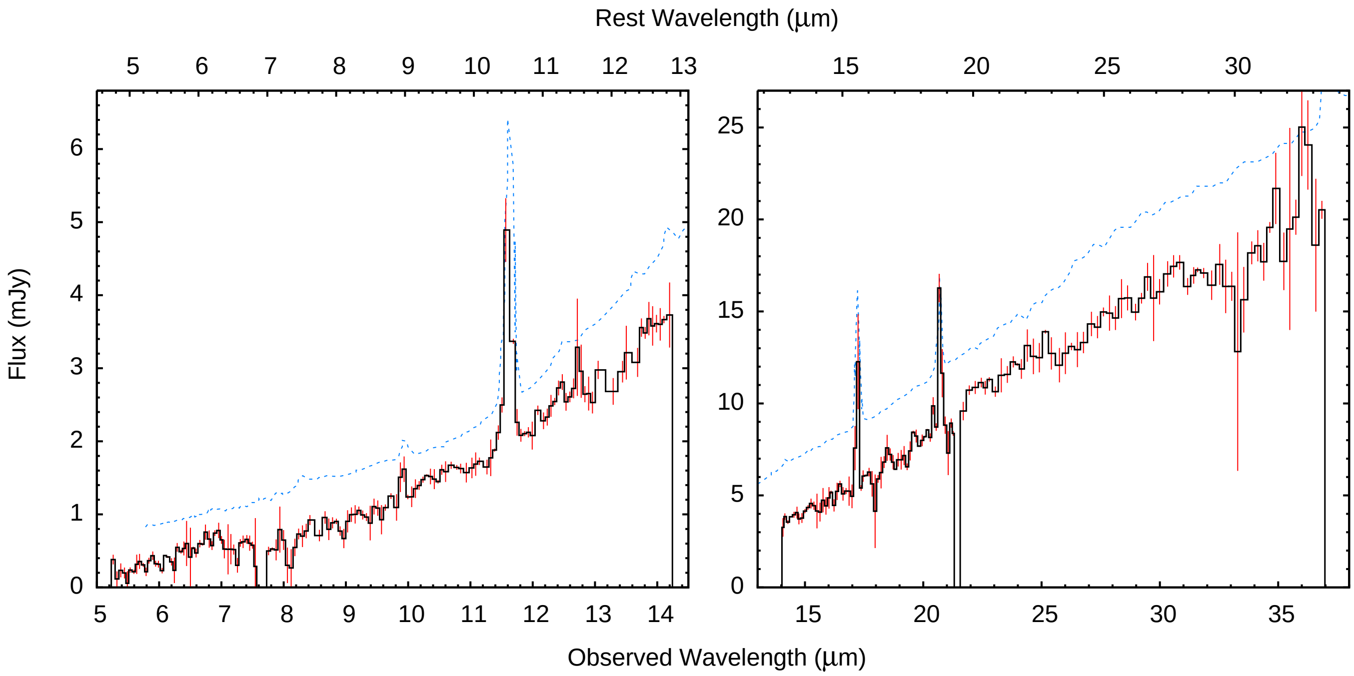


**Figure 1.** Low-resolution IRS spectrum of the host galaxy of GRB 031203. Orders 1 and 2 of the SL (left) and LL (right) modules. Thin red lines indicate uncertainties on the spectrum. Strong fine structure lines typical of a young star-forming galaxy are detected (see Fig. 2 for close-ups of the lines as observed with the high-resolution modules). Very high-ionisation fine structure lines, indicative of AGN activity (e.g. [Ne V] 14.3 $\mu$m or [O IV] 25.89 $\mu$m, Tommasin et al. 2010), are not found. The IRS spectrum of the blue compact dwarf galaxy II Zw 40 from Wu et al. (2006) is plotted (dashed line), scaled and offset, for comparison purposes.

data were obtained. Calibrator sources PKS B1934–638 and PKS B0826–373 were utilized to set the absolute flux calibration of the array and to calibrate phases and gains, respectively. Data reduction and analysis was done using the MIRIAD package (Sault & Killeen 2004). The final synthesized beam sizes for 20 and 13 cm images were $8\farcs5 \times 3\farcs4$ and $6\farcs3 \times 2\farcs3$, respectively, with root-mean-square (rms) values of 46 and 37 $\mu$Jy beam$^{-1}$. The flux density of HG 031203 was estimated by fitting a two-dimensional Gaussian function to the data with its centroid, size, and orientation as free parameters.

We obtained submillimeter (870 $\mu$m) observations on 13–18 August 2008 using the Large Apex BOlometer CAmera (LABOCA; Siringo et al. 2009) mounted at the Atacama Pathfinder Experiment (APEX; Güsten et al. 2006). A total of 7 hr of on-source data were obtained. The weather condition varied between 0.3–1.4 mm of precipitable water vapour. Data reduction and analysis was done using the miniCRUSH package (Kovács 2008)[11]. We used the 'deep' option that results in the best signal-to-noise ratio for faint, point-like objects. The beam size for the final image was $19\farcs5$ and the rms was 2.2 mJy beam$^{-1}$. The target was not detected.

## 3. RESULTS

*Spitzer*, APEX and ATCA each provide photometry or photometric limits at long wavelengths, allowing us to determine the extinction-free emission from HG 031203. These data are presented in Table 2. The *Spitzer* photometric detections are consistent with the flux-calibrated IRS spectra at the same wavelengths.

### 3.1. *Spitzer spectroscopy*

[11] `http://www.submm.caltech.edu/~sharc/crush/`

**Table 2**
Spitzer, APEX, and ATCA photometry of HG 031203

| Instr. | IRAC ($\mu$Jy) | | MIPS (mJy) | | APEX (mJy) | ATCA ($\mu$Jy) | |
|---|---|---|---|---|---|---|---|
| Band | 3.6 $\mu$m | 5.8 $\mu$m | 24 $\mu$m | SED | 870 $\mu$m | 13 cm | 21 cm |
| Flux | $193 \pm 2$ | $356 \pm 13$ | $11.3 \pm 0.4$ | $< 40$ | $< 12$ | $191 \pm 37$ | $254 \pm 46$ |

**Table 3**
Principal emission lines in the mid-IR spectrum of HG 031203

| Line ID | Wavelength ($\mu$m) | Flux ($10^{-15}$ erg cm s$^{-1}$) |
|---|---|---|
| [S IV] | 10.51 | $8.5 \pm 1.5$ |
| [Ne II] | 12.81 | $0.7 \pm 0.2$ |
| [Ne III] | 15.56 | $10.6 \pm 1.1$ |
| [S III] | 18.71 | $5.2 \pm 0.7$ |

The most striking features of the IRS spectra of HG 031203 (Fig. 1) are clearly the strong forbidden lines, [S IV] 10.51 $\mu$m, [S III] 18.71 $\mu$m, [Ne III] 15.55 $\mu$m, and [Ne II] 12.81 $\mu$m (Fig. 2 and Table 3).

Comparing our spectrum to spectra of other star-forming galaxies (Wu et al. 2006), it is immediately apparent that the broad features at 6.2, 7.7, 8.6 and 11.2, 12.7, and 16.4 $\mu$m, believed to be associated with polycyclic aromatic hydrocarbons (PAHs, Tielens 2008), are, somewhat surprisingly, not detected. The lack of PAH emission could be indicative of a very strong continuum from an active galactic nucleus (AGN) diluting the PAH features, a discriminant noticed with ISO (e.g. Lutz et al. 1998; Laureijs et al. 2000). The presence of an AGN is claimed by Levesque et al. (2010), however, even at first glance this seems unlikely since the PAH emission ap-

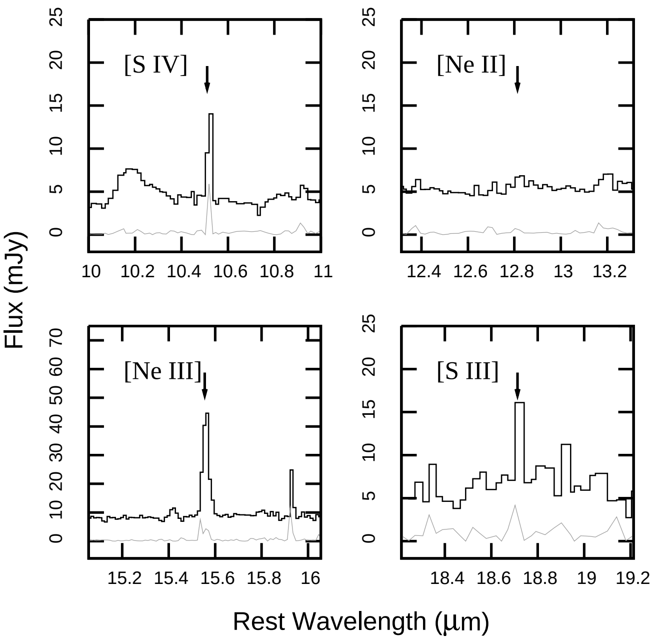


**Figure 2.** The locations of the most prominent mid-IR fine structure lines typically found in star-forming galaxies from the high-resolution, SH and LH, modules. The grey lines indicate the associated uncertainty at each wavelength. The broad feature at 10.2 $\mu$m is undetected in the SL spectrum and is related to an unremoved artefact in our SH data.

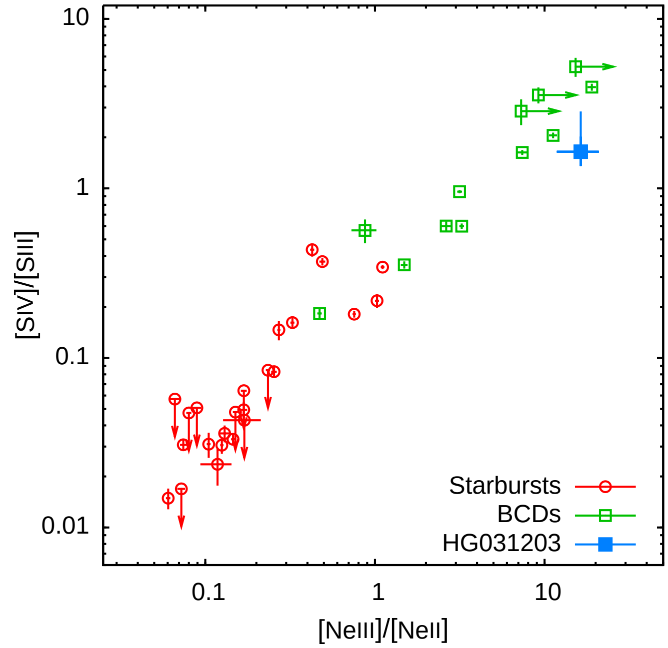


**Figure 3.** Line ratios of star-forming galaxies. The starburst galaxy sample of Bernard-Salas et al. (2009) are plotted as circles. A sample of blue compact dwarf galaxies, which have younger dominant stellar populations, higher specific star-formation rates, and harder radiation fields even than the starburst galaxies, is also plotted (open squares, Wu et al. 2006). HG 031203 (filled square) is among the most extreme of the blue compact dwarf galaxies, indicating that its dominant stellar population is extremely young. The fact that the diagnostic lines are in the mid-IR ensures that the diagnostics are not significantly affected by dust obscuration.

pears to be simply absent, rather than diluted by a powerful continuum. We address the other lines of evidence that essentially rule out a significant AGN contribution in this galaxy below. The other possibility is that the galaxy is a powerful starburst. In such galaxies, it is well-known that the PAH flux is anti-correlated with the hardness of the radiation field, either because young star-forming populations do not form PAHs, or because the hard radiation field destroys them (Wu et al. 2006). This seems consistent with our findings from the mid-IR and optical–near-IR spectra below.

The ratios of the forbidden lines, associated with the excitation state of the gas in the interstellar medium of the galaxy, indicate the hardness of the radiation field. In Fig. 3 we show the [S IV]/[S III] flux ratio ($1.6^{+1.2}_{-0.3}$) as a function of [Ne III]/[Ne II] ($16.3 \pm 4.5$), and compare HG 031203 to samples of starburst galaxies and blue compact dwarf galaxies (BCDs). The spectrum shows no indication of absorption at 9.7 $\mu$m from silicates, neither does it show any hint of the higher excitation lines that might be expected from an AGN such as [Ne V] 14.3 $\mu$m or [O IV] 25.9 $\mu$m (Tommasin et al. 2010). All of these facts point to HG 031203 being a purely star-forming galaxy, but with an exceptionally hard radiation field, indicating a very young stellar population, probably $\lesssim 10$ Myr (Madden 2000). The fact that these ratios are observed in the MIR suggests that the galaxy has essentially the same character throughout, i.e. that it is dominated in the MIR by the same young stellar population that dominates in the optical (see below).

### 3.2. *X-shooter spectroscopy*

The X-shooter spectra are very information-rich (Fig. 4), containing many strong emission lines with a resolving power high enough to look in some detail at the interstellar medium (ISM) in this galaxy. However in this paper we will address ourselves primarily to the continuum, with regard to the analysis of the SED of the galaxy in order to determine the dominant emission processes and the overall nature of the ISM. In this regard, we have also determined the ratios of the fluxes of nebular lines, to determine the nature of the source powering the optical emission: [O II], H$\beta$, [O III], [S II], [N II], and [O I]. The relevant line ratios are: log([O III]/H$\beta$) = $0.77 \pm 0.02$, log([S II]/H$\alpha$) = $-1.23 \pm 0.02$, log([N II]/H$\alpha$) = $-1.35 \pm 0.02$, log([O I]/H$\alpha$) = $-2.02^{+0.06}_{-0.07}$, and log([O III]/[O II]) = $0.78^{+0.06}_{-0.07}$ .

These high-quality ratios resolve the debate about the presence of an AGN in HG 031203. While the line ratios do indicate a very hard radiation field in the ISM of this galaxy, making it among the most extreme starburst galaxies consistent with the MIR line ratios, they unequivocally locate it in the star-forming region of the Baldwin-Phillips-Terlevich (BPT, Baldwin et al. 1981) excitation diagrams (see Kewley et al. 2006, and references therein), contrary to a recent claim (Levesque et al. 2010), and consistent with previous findings of a pure starburst (Prochaska et al. 2004; Margutti et al. 2007; Han et al. 2010). Our similar finding from the mid-IR spectrum above on the absence of AGN characteristics, indicates that there is no very different obscured component.

The presence of a break in the spectrum at 4000 Å is an indication of the age of the stellar population (Bruzual & Charlot 2003). We quantified the break in HG 031203 using the definition of D4000 of Balogh et al. (1999), finding D4000 = $0.93 \pm 0.05$. This effectively means that there is no 4000 Å break, and indicates a continuum dominated by a very young stellar population, probably younger than $\sim 10$ Myr, with a high specific star-formation rate (Brinchmann et al. 2004; Gallazzi et al. 2005).

### 3.3. *The spectral energy distribution of HG 031203*

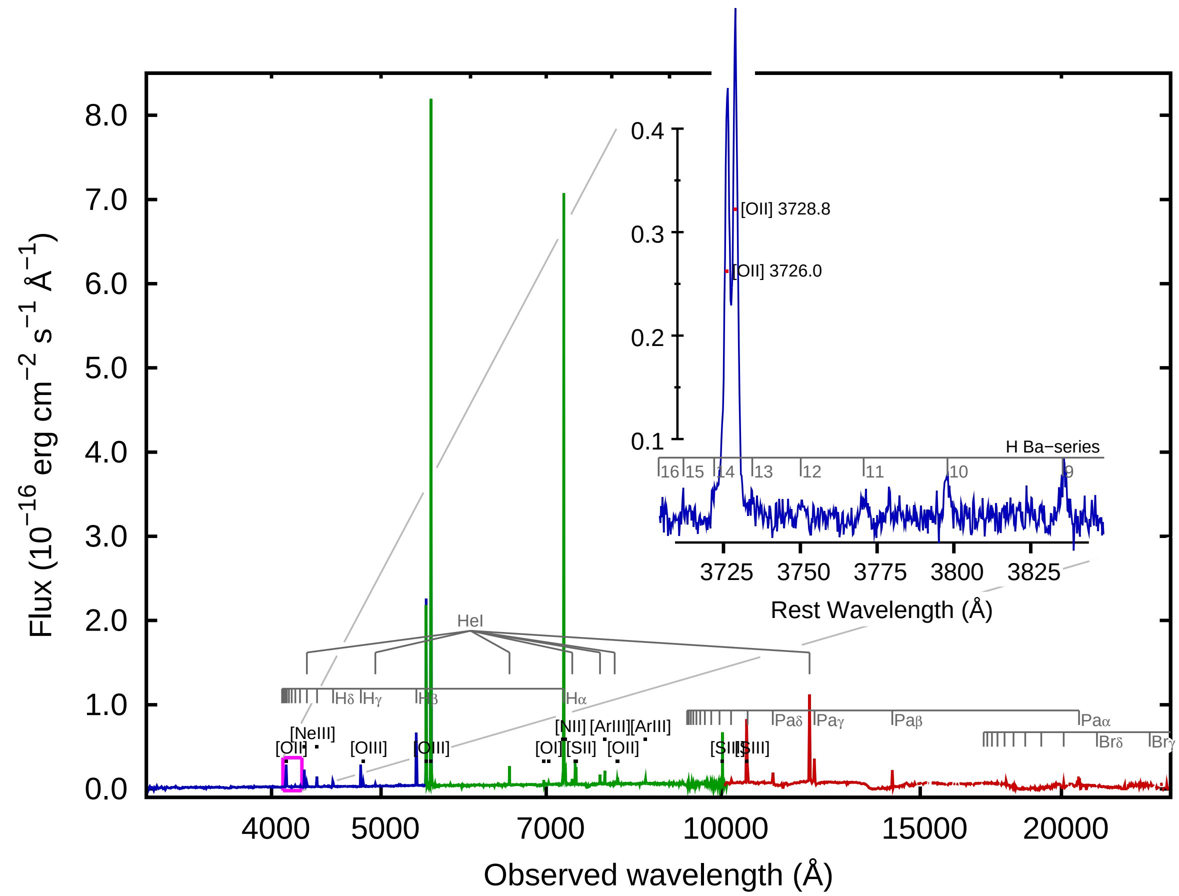


**Figure 4.** The X-shooter spectrum of HG 031203. Strong nebular emission dominates the spectrum.

The combination of 0.3–2.5 $\mu$m spectroscopy from X-shooter and 5–35 $\mu$m spectroscopy from the IRS, combined with limits in the FIR and sub-mm and detections at radio wavelengths, allow us to get a fairly complete picture of the properties of HG 031203 via its SED (Fig. 5).

### 3.3.1. *Foreground dust extinction*

The first outstanding question is the Galactic dust obscuration toward this galaxy. The Balmer decrement, which, due to the low redshift, essentially gives us the total reddening along the line of sight, yields E($B-V$) = 1.17 (Prochaska et al. 2004): it is not entirely clear, however, what fraction of this extinction is in the Galaxy and what fraction is in HG 031203. Before discussing the foreground extinction, it should be noted that our main results for HG 031203 are insensitive to the precise value of the extinction fraction in our Galaxy. The mid-IR emission is largely unaffected by this level of extinction. Our primary age indicator for the galaxy population, D4000, is also insensitive to the precise extinction correction applied, as are the most important optical line ratios since they lie very close in wavelength space (e.g. O III/H$\beta$).

The dust maps of Schlegel et al. (1998) yield E($B-V$) = 1.04 in the Galaxy alone in this direction and this value has been used by several groups (Thomsen et al. 2004; Gal-Yam et al. 2004; Malesani et al. 2004; Cobb et al. 2004). While these measurements seem to imply that the correction factor to obtain the intrinsic galaxy spectrum is E($B-V$) = 1.04, Prochaska et al. (2004) and Margutti et al. (2007) in fact argue that the value from Schlegel et al. (1998) is overestimated along this sightline and suggest the foreground Galactic extinction is E($B-V$) = 0.7–0.8, with E($B-V$) $\sim$ 0.3–0.4 residing in HG 031203. Recently, Schlafly et al. (2010) have indicated that the global normalisation for E($B-V$) in Schlegel et al. (1998) may be overestimated by $\sim$ 14%. There are, however, significant variations in the normalisation over the sky ($\sim$ 20%): in particular, in this direction in longitude, the normalisation is somewhat higher, but for high E($B-V$) sightlines, the normalisation is somewhat lower. Furthermore, for very high extinction sightlines, the extinction-estimation method used is not effective. This leaves the situation somewhat confused.

Another line of attack to address the level of the Galactic extinction is to use the Leiden-Argentine-Bonn Galactic H I maps, which indicate a column density of $5.0 \times 10^{21}$ cm$^{-2}$ in this direction (Kalberla et al. 2005). The gas to dust correlation of Predehl & Schmitt (1995) and more recently Vuong et al. (2003), suggest an E($B-V$) of 0.91 and 1.03 respectively, assuming standard ISM abundances; but the measurement is abundance sensitive and may be lower by 20% for a different choice of metallicity (Vuong et al. 2003). The situation is therefore still complex.

However, in fitting the SED of HG 031203, we find that the total star-formation rate (SFR) is strongly inconsistent (larger than a factor of two) with the H$\alpha$-derived SFR if we assume a low Galactic extinction (E($B-V$)=0.78). We require an extinction close to the value of Schlegel et al. (1998) to reconcile the SED-derived SFR with the SFR derived from H$\alpha$ by Prochaska et al. (2004) and Margutti et al. (2007). However,

the presence of a significant MIR dust emission in HG 031203 suggests that the UV light suffers some dust extinction in the host, and our modelling of the full SED suggests $A_V$ of a few tenths of magnitudes (see below). This is consistent with the observed Balmer decrement since it adds relatively little ($E(B-V) \sim 0.1$) to the overall reddening. On the basis of these arguments, we simply use $E(B-V) = 1.04$, the value from the Schlegel et al. (1998) dust maps, to correct for Galactic foreground extinction in our analysis of the HG 031203 SED.

#### 3.3.2. *Comparison to active blue compact dwarf galaxies*

The strong nebular emission lines, extreme hard line ratios, lack of PAH emission features, and probable hot dust temperature, suggest a close similarity between HG 031203 and blue compact dwarf galaxies. This suggestion was made by Sollerman et al. (2005) when analysing the optical properties of low redshift SN-GRB host galaxies, including HG 031203. In particular, HG 031203 is similar to those classified as being in an "active" mode of star-formation (e.g. Hunt et al. 2005). The IR line ratios in fact, suggest that HG 031203 is among the more extreme BCDs in terms of the hardness of its radiation field (Fig. 3). A striking similarity exists in the mid-IR emission of HG 031203 and II Zw 40, which has a very similar metallicity and line ratios (Wu et al. 2008) and a nearly identical IRS spectrum in terms of slope and strength of features (Wu et al. 2006). We have plotted the SED of II Zw 40 from Hunt et al. (2005) on top of the SED of HG 031203 in Fig. 5 scaled by the ratio of the [Ne III] 15.6 $\mu$m line fluxes. It is clear that it is only in the mid-IR that the spectral similarity holds. The UV/optical continuum of II Zw 40 is considerably bluer; its IR peak is brighter than is possible for HG 031203, and is likely somewhat cooler. Both facts might be explained by a distribution of dust in II Zw 40 that is different, possibly distributed more uniformly, and less densely located in star-forming regions than is the case in HG 031203.

#### 3.3.3. *Modelling the SED*

We attempted to fully reproduce the UV–radio SED of HG 031203 using the GRASIL code (Silva et al. 1998). The best-fitting SED model (see Fig. 5) was obtained with the fitting procedure outlined in Michałowski et al. (2010a) using the templates of Iglesias-Páramo et al. (2007) and Michałowski et al. (2008) with the PAH emission removed and restricting the time of the total galaxy evolution to 200 Myr. This attempt failed to reproduce the SED on two points. First the observed 3.6 $\mu$m flux was too high with respect to any of the models. This excess is well-known in dwarf galaxies and is speculated to be due to a hot dust component, strong Br$\alpha$ emission, or nebular continuum emission (Smith & Hancock 2009). Given the effect of the very strong nebular emission lines on other photometric datapoints (e.g. the elevated $V$-band magnitude, Fig. 5), line emission from Br$\alpha$ may be sufficient to explain the observed 3.6 $\mu$m excess here. The second point of failure relates to the 4000 Å break, where none of the templates could reproduce the lack of a break in the spectrum HG 031203, in spite of the restriction to younger stellar templates.

Finally, the dust mass is not very well-constrained with this dataset, since we do not quite cover the peak of the thermal emission component. An indication of a turnover in the IRS spectra at the longest wavelengths (Fig. 5) suggests the peak dust temperature is very high, as observed in dwarf galaxies (Galametz et al. 2009), perhaps hotter even than the 45 K suggested for sub-mm–detected GRB hosts (Michałowski et al. 2008). However our constraints at longer wavelengths do not allow us to exclude a large cool dust component.

## 4. DISCUSSION

We have found that HG 031203 is an extreme star-forming galaxy, similar to, but considerably more luminous than, nearby blue compact dwarf galaxies. A very hard radiation field is found from both optical and mid-infrared line ratios, and is consistent with a very young star-forming population. In spite of its blue optical continuum, approximately as much energy is reradiated by dust as comes directly from stars. This suggests a strongly non-uniform dust distribution in the galaxy.

The host galaxy of GRB 031203 is among the brighter GRB hosts known because of its low redshift and intrinsic luminosity. Despite a high foreground extinction, it was already well-characterised in the optical, showing a high star-formation rate and relatively low metallicity. Margutti et al. (2007) suggest it is somewhat atypical of the few nearby GRB hosts so far observed in that it lies, at low-metallicity and relatively high luminosity, off the luminosity-metallicity locus of KPNO International Spectroscopic Survey galaxies. The deviation might be explained simply by the low pre-existing stellar mass in this galaxy. According to the fundamental plane for star-forming galaxies of Mannucci et al. (2010); Lara-López et al. (2010), HG 031203 should have a stellar mass of approximately $\log(M_*/M_\odot) \sim 9.5$, similar to the value obtained by Castro Cerón et al. (2010).

Initial samples of gamma-ray burst host galaxies suggest they are typically sub-luminous and blue (Le Floc'h et al. 2003) with young ages (Christensen et al. 2004), high specific star-formation rates (Castro Cerón et al. 2006; Savaglio et al. 2009; Svensson et al. 2010; Chary et al. 2002) and irregular morphologies (Fruchter et al. 2006). All of these conclusions however have been based on rather incomplete and arbitrarily selected galaxy samples, affected by strong optical/UV selection bias because of the requirement to have a detection of an optical afterglow to localise the burst to a high enough accuracy to identify the host. On the other hand, analyses of the hosts of bursts believed to be dust-obscured are consistent with this picture—sub-mm and radio observations yield only a small fraction of detections of these targeted bursts (Tanvir et al. 2004; Berger et al. 2003) and star-formation limits found in the radio (Michałowski et al. 2008) and X-ray (Watson et al. 2004) show no evidence of very high star-formation rates—suggesting that even the hosts of obscured bursts are not typically ultraluminous IR galaxies (ULIRGs). In particular, the hosts of GRBs at low redshifts are consistent with this general outline (Sollerman et al. 2005; Michałowski et al. 2009; Thöne et al. 2008; Wiersema et al. 2007), which means that despite the strong evolution of star-forming galaxies from $z \gtrsim 3$ to $z = 0$, GRBs offer a good way of targeting closer sites of very young star-formation that are typical of galaxies in the early universe (e.g. Kocevski et al. 2009).

### 4.1. *HG 031203 as a high-redshift star-forming galaxy*

HG 031203 may offer a good low-redshift archetype of high-redshift star-forming galaxies. Its extremely young age, blue optical continuum, and low stellar mass bears a striking resemblance to models of $z$ and $Y$-band drop-outs detected with *HST*. A $z \sim 2$ analogue of these galaxies was suggested recently by Erb et al. (2010), and it is interesting to note that HG 031203 has emission line ratios and estimated stellar mass very similar to that galaxy. Furthermore, the fact

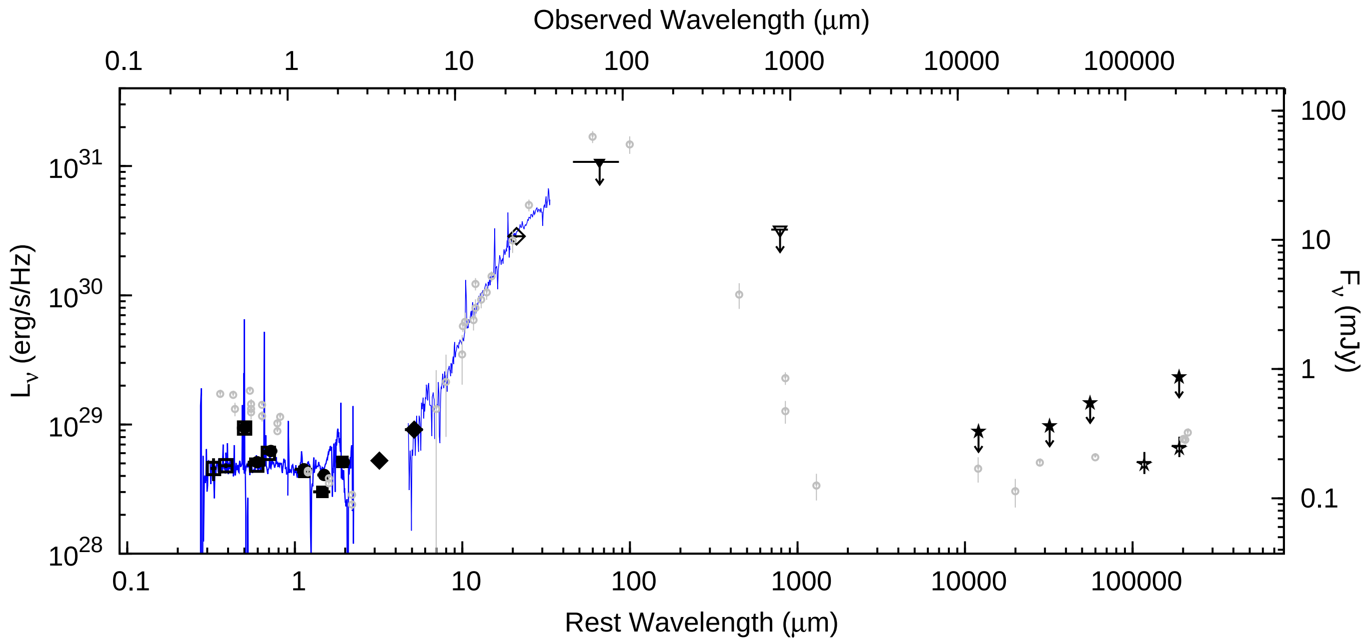


**Figure 5.** The SED of the host galaxy of GRB 031203. The continuous lines (blue) are the X-shooter and *Spitzer*-IRS spectra, open and closed squares are optical (Margutti et al. 2007) and near-IR (Prochaska et al. 2004) photometry respectively, while closed circles represent additional optical and near-IR photometry from Malesani et al. (2004) respectively. Data from *Spitzer*-IRAC (diamonds) and MIPS-24 $\mu$m (open diamond) as well as ATCA (open stars) are also plotted. Finally, upper limits are shown from MIPS-SED mode (filled, down triangles), APEX 870 $\mu$m (open, down triangles) and VLA (filled stars, Soderberg et al. 2004). The SED has been corrected for a Galactic extinction of E($B-V$)=1.04. Marked in small open circles (grey), is the SED of the actively–star-forming blue compact dwarf galaxy II Zw 40 which has a similar metallicity and radiation field. Its SED is scaled by a factor of 17, the ratio of the [Ne III] 15.6 $\mu$m emission lines. The best-fit SED template modelled with the GRASIL code is plotted as a dotted line.

that HG 031203 was selected by the presence of a GRB—known to be associated with the deaths of massive stars, and now among the most distant spectroscopically-confirmed objects—adds to the interest with which HG 031203 must be held as a nearby example of the high-redshift mode of massive star-formation.

Our data on HG 031203 bear on the current debate surrounding the SEDs of $z\sim7$ and $z\sim8$ galaxies detected via $z$ and $Y$-band drop-outs. It has been suggested that the elevated fluxes (above the extrapolation of the restframe UV continuum) redward of the 4000 Å break in these objects as observed by IRAC in stacked 3.6 and 4.5 $\mu$m images, are indicative of a substantial 4000 Å/Balmer break. From these detections a stellar age of $\sim300$ Myr is inferred for these galaxies (Labbé et al. 2010b,a; Bouwens et al. 2010). However it has been pointed out, and demonstrated via stellar synthesis models, that nebular line emission, in particular very strong [O III] lines, can produce an elevation in the IRAC bands similar to that observed (Schaerer & de Barros 2010; Ono et al. 2010). Using models containing nebular line emission, a population as young as 5 Myr provides a reasonable fit to the data (Schaerer & de Barros 2010). The question of old stellar populations in galaxies at $z\sim7-8$ is critically important, as it has a strong bearing on when the first population of stars formed and whether these stars formed at a time that could have allowed them to cause reionisation. While it has been argued on a number of grounds that the elevated IRAC fluxes are indeed related to an old stellar population in these very early galaxies (Bouwens et al. 2010), the arguments are circumstantial and the subject is still open.

In Fig. 6 we overplot the SED from Labbé et al. (2010b) of faint $z\sim7$ drop-out galaxies (scaled by 0.36), on the SED of HG 031203. The approximate similarity in UV slope (though there is some uncertainty here due to the high foreground Galactic dust column), in the total luminosity, and in the relative elevation of the broadband fluxes, show clearly that HG 031203 is indeed a reasonable analogue of these $z\sim7$ candidates. Furthermore, we see in this analogue precisely the broadband photometry behaviour suggested by the modelling of Schaerer & de Barros (2010). The effect only occurs because of the stacking of sources. At $z=7$, the line lies in neither IRAC band, but the stacking of sources in the range $z=6.4-7.4$ and the relatively rectangular shape of the bandpasses raises both IRAC bands.

Lastly, in spite of the very young stellar age indicated by the lack of a 4000 Å break, HG 031203 is clearly dusty, with as much emission from star-formation emerging in the mid-IR via dust-reprocessing as there is emerging in the UV. The best-fit GRASIL model also suggests that the UV emission is still significantly obscured ($A_V\sim0.3$), although it is obvious that this must be the case from the mid-IR emission. This latter point also echoes the claim from Schaerer & de Barros (2010) based on modelling, that drop-out galaxies at $z\sim7$ may still be substantially obscured in spite of their blue continua. From sub-mm and mm observations, we are already aware of the presence of large quantities of dust at $z\sim6$ in QSOs. However, the possible presence of dust in significant quantities in very young galaxies at $z\sim7$, suggests that dust is formed very rapidly. Typically, very rapidly is taken to mean a few hundred million years (e.g. Dwek et al. 2007; Valiante et al. 2009). However, if the dust is formed in association with the formation of stars, whether in SNe (Dwek et al. 2007; Dunne et al. 2003, 2009), or grown in the ISM (Draine 2009; Michałowski et al. 2010c,b) the timescales could in principle be as short as several million years. This has major implications for the detection of galaxies of this luminosity with NIRCAM, NIRSPEC and MIRI onboard *JWST* at $z\sim7$–10.

## 5. CONCLUSIONS

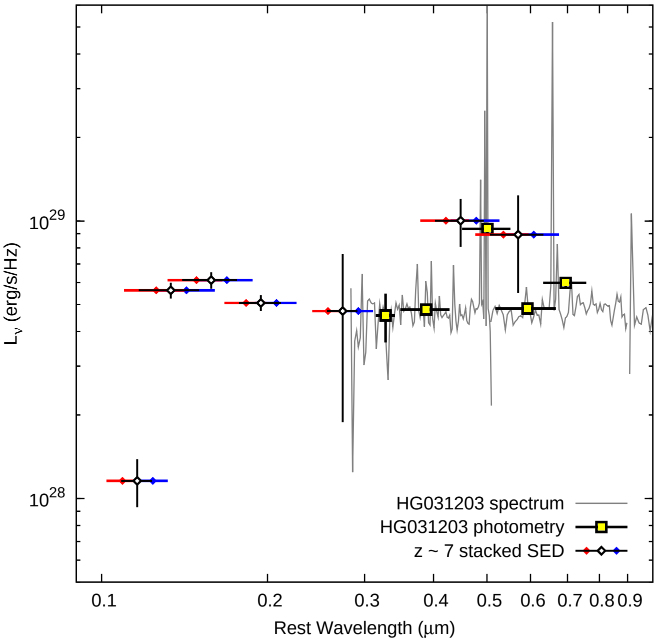


**Figure 6.** The UV-optical SED of the host galaxy of GRB 031203 (grey solid line and black open squares). The $V$-band photometry is clearly strongly elevated simply due to the [O III] emission lines. Overplotted (diamonds) is the stacked SED of faint $z \sim 7$, $z$-band dropouts from Labbé et al. (2010b) scaled by 0.36 to match the luminosity of HG 031203. The blue and red diamonds represent redshifts of 6.4 and 7.4 respectively, indicating the approximate range of rest wavelengths entering the stacked filters. The elevation of photometry near the [O III] lines and the slope of the UV-optical continuum are similar in both SEDs suggesting the galaxies have similar dominant stellar ages, $\lesssim 10$ Myr.

We have presented the first mid-IR spectrum of a GRB host galaxy as well as the first X-shooter spectrum of a GRB host. These spectra show strong nebular lines associated with recent star-formation, but no PAH features. We conclude that HG 031203 is an extreme star-forming galaxy with a radiation field among the hardest known for such a galaxy, in both its obscured and unobscured regions. The broadband SED of HG 031203 has a moderate luminosity dust emission peak, likely with a high temperature, similar to local blue compact dwarf galaxies. If dust can be formed in association with supernovae, it is possible that such a dust peak may exist even in very young galaxies in the early universe, making such galaxies potentially much easier to detect with *JWST*. The lack of a 4000 Å break and the high-ionisation emission line ratios in the MIR spectrum of HG 031203 suggests a dominant stellar age $\lesssim 10$ Myr. HG 031203 has a UV-optical SED similar to $z$-band dropout galaxies at $z \sim 7$. This and its very young age indicate that this GRB host galaxy at $z \sim 0.1$ may be an excellent analogue of the population of star-forming galaxies at very high redshifts currently being discovered by *HST*.

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